

Age constraints in the double pulsar system J0737–3039

D.R. Lorimer^{1,*}, P.C.C. Freire², I.H. Stairs³, M. Kramer⁴, M.A. McLaughlin,¹
M. Burgay,⁵ S.E. Thorsett,⁶ R.J. Dewey,⁶ A.G. Lyne,⁴ R.N. Manchester,⁷
N. D’Amico,⁵ A. Possenti⁵ and B.C. Joshi⁸

¹*Department of Physics, West Virginia University, Morgantown, WV 26506, USA*

²*NAIC, Arecibo Observatory, HC3 Box 53995, Arecibo, PR 00612, USA*

³*Department of Physics and Astronomy, University of British Columbia, 6224 Agricultural Road, Vancouver, BC V6T 1Z1, Canada*

⁴*INAF - Osservatorio Astronomica di Cagliari, 09012 Capoterra, Italy*

⁵*University of Manchester, Jodrell Bank Observatory, Macclesfield, Cheshire, SK11 9DL, UK*

⁶*Department of Astronomy and Astrophysics, University of California, Santa Cruz, CA 95064, USA*

⁷*ATNF, CSIRO, PO Box 76, Epping, NSW 2121, Australia*

⁸*NCRA, PO Box Bag 3, Ganeshkhind, Pune 411007, India*

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ABSTRACT

We investigate the age constraints that can be placed on the double pulsar system using models for the spin-down of the first-born 22.7-ms pulsar A and the 2.77-s pulsar B with characteristic ages of 210 and 50 Myr respectively. Standard models assuming dipolar spin-down of both pulsars suggest that the time since the formation of B is ~ 50 Myr, i.e. close to B’s characteristic age. However, adopting models which account for the impact of A’s relativistic wind on B’s spin-down we find that the formation of B took place either 80 or 180 Myr ago, depending the interaction mechanism. Formation 80 Myr ago, closer to B’s characteristic age, would result in the contribution from J0737–3039 to the inferred coalescence rates for double neutron star binaries increasing by 40%. The 180 Myr age is closer to A’s characteristic age and would be consistent with the most recent estimates of the coalescence rate. The new age constraints do not significantly impact recent estimates of the kick velocity, tilt angle between pre and post-supernova orbital planes or pre-supernova mass of B’s progenitor.

Key words: methods: statistical; pulsars: individual J0737–3039A; pulsars: individual J0737–3039B; binary systems: evolution

1 INTRODUCTION

In addition to its use as a laboratory for studying general relativity and plasma physics, the double pulsar system J0737–3039 (Burgay et al. 2003; Lyne et al. 2004) provides new insights into the evolution of massive binary systems. In the standard model for binary pulsar formation (for a recent review, see van den Heuvel 2007), double neutron star systems are formed from massive binary systems where the initially more massive (primary) star evolves off the main sequence and undergoes a supernova explosion to form a neutron star. During the evolution of the initially less massive (secondary) star, the first-born neutron star accretes matter and gains angular momentum spinning it up to short periods and (through poorly understood processes; Shibasaki et al. 1989) reducing its magnetic field. If the secondary is sufficiently massive to explode as a supernova, and the binary

system survives this explosion, the resulting system is a pair of neutron stars: a short-period recycled pulsar from the primary and a young “normal” pulsar from the secondary.

The double pulsar system J0737–3039 where a recycled 22.7-ms pulsar (hereafter A) is observed in a 2.4-hr orbit around a 2.77-s pulsar (hereafter B) presents a new opportunity to study this model. We use the current spin parameters of the two pulsars, together with models for their spin-down evolution, to place constraints on the age of the system. The motivation for this work is twofold. Firstly, a better constraint on the system age would reduce the uncertainties in empirical studies of the rate of binary neutron star inspirals — one of the key sources for gravitational wave observatories (see, e.g., Kim et al. 2006, and references therein). Secondly, because the age can be used to directly compute the post-supernova orbital parameters, we may be able to better constrain B’s progenitor mass and in turn improve our understanding of the formation of this unique binary system (Piran & Shaviv 2005; Willems et al. 2006;

* Email: Duncan.Lorimer@mail.wvu.edu

Table 1. Summary of the model assumptions used in this paper.

Model	Interaction modeled?	n_A	n_B	Torque decay
1	no	0.0–5.0	1.4–3.0	none
2	no	3.0	3.0	B: 10 Myr
3	no	3.0	3.0	B: 100 Myr
4	yes	0.0–5.0	1.0	none
5	yes	0.0–5.0	2.0	none

Stairs et al. 2006). A preliminary version of these results was presented Lorimer et al. (2005). In this paper, we consider models which account for the modification of B’s spin by A’s relativistic wind. Following a brief review of the properties of J0737–3039 in Section 2, we derive age constraints based on various spin-down models for both pulsars in Section 3 and discuss their implications in Section 4.

2 J0737–3039 AND THE STANDARD MODEL

Applying the binary recycling scenario to the double pulsar system, we identify A as the first-born neutron star which was spun up (recycled) by the mass accretion process. B is then the neutron star formed during the supernova explosion of the secondary. Using the observed spin parameters of both pulsars to estimate their surface magnetic fields $B_{\text{surf}} = 3.2 \times 10^{19} \text{ G} \sqrt{P\dot{P}}$, we find $B_{\text{surf},A} = 6.3 \times 10^9 \text{ G}$ and $B_{\text{surf},B} = 1.2 \times 10^{12} \text{ G}$. That A’s field is some three orders of magnitude lower than that of B is in accord with the recycling hypothesis — i.e. the weaker field of A is a consequence of the recycling process. We note however, that due to the interaction of A’s wind which penetrates deep into B’s magnetosphere (Lyne et al. 2004), some care should be taken when interpreting the exact value of B’s magnetic field. Arons et al. (2005) have proposed a model in which A’s wind exerts a propellor torque on B which dominates its spin-down. In this case, the implied magnetic field strength of B is a factor of three lower than the above dipole estimate.

After the accretion phase, it is assumed that both neutron stars have been spinning down due to a steady braking torque; as such they represent independent clocks measuring the time since accretion ceased. A straightforward test of the prediction is to use the characteristic ages of A and B: $\tau_A = P_A/(2\dot{P}_A)$ and $\tau_B = P_B/(2\dot{P}_B)$. Lyne et al. (2004) find $\tau_A = 2.1 \times 10^8 \text{ yr}$ and $\tau_B = 0.5 \times 10^8 \text{ yr}$. Possible explanations for this discrepancy are: (i) the standard evolutionary scenario does not apply; (ii) as observed in other pulsars (see, e.g., Kramer et al. 2003) characteristic ages are not reliable due to their simplifying assumptions; (iii) both the model and the characteristic ages are wrong.

Given the circumstantial evidence in favour of the recycling hypothesis, and the absence of viable alternative models, the simplest resolution is option (ii). In the rest of this paper, we investigate the consequences of this case and show that, when the simplifying assumptions of the characteristic ages are taken into account, the apparent age differences of the two pulsars can be reconciled.

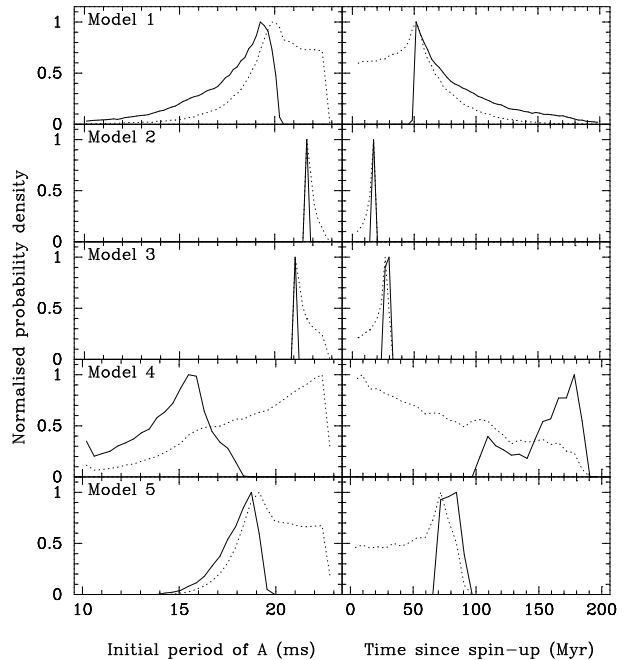


Figure 1. Probability density functions showing the post-accretion spin period of A (left panels) and the time since the end of the spin-up phase (right panels). For each model, we assume a range of initial spin periods for B to be anywhere between zero and B’s current period (dotted curves), and between zero and 150 ms (solid curves).

3 MODELING THE SPIN EVOLUTION AND AGES OF A AND B

Our goal is to use the observed parameters and models for the spin-down of the two neutron stars in J0737–3039 to place constraints on the system age and pulsar birth parameters. Before describing specifics, we first outline our general approach. For each pulsar, we consider a generic spin-down model of the form

$$\dot{P} = KP^{2-n}, \quad (1)$$

where P is the spin period, n is the braking index (for spin-down due to magnetic dipole radiation, $n = 3$) and the factor K depends on the neutron star moment of inertia, braking torque applied to the star and, for some models of B’s spin evolution, the effect of A’s relativistic wind. To distinguish between each pulsar, we add A and B subscripts where appropriate. Our basic approach is to apply and solve the equation under certain model constraints to find the ‘spin-down’ age of each pulsar, $t_{\text{sd},A}$ and $t_{\text{sd},B}$. Table 1 summarizes the different models we investigated.

A key assertion we then make is that the spin-down age for A, $t_{\text{sd},A}$, refers to the time since spin-up ceased, and is essentially the same epoch as B began life as a pulsar. We therefore assume

$$t_{\text{sd},A} = t_{\text{sd},B}. \quad (2)$$

Since this condition is only met for certain sets of birth parameters, we can use it to find the most probable age of the system assuming a given set of model assumptions. Our results are summarized in Fig. 1 and discussed in detail in the following subsections.

3.1 Constant braking parameters

In the simplest case, where K and n are independent of time, equation (1) can be integrated directly to find t_{sd} . For the case $n = 1$, we find

$$t_{\text{sd}} = 2\tau \ln \left(\frac{P}{P_0} \right), \quad (3)$$

while, for all other values of n , the solution is

$$t_{\text{sd}} = \frac{2\tau}{(n-1)} \left[1 - \left(\frac{P_0}{P} \right)^{n-1} \right]. \quad (4)$$

Here, P_0 is the initial spin period and the characteristic age $\tau = P/2\dot{P}$. Since the current period and period derivative are readily observable through timing observations, the unknown parameters are n and P_0 for each pulsar.

We explore the parameter space using a Monte Carlo simulation to compute the spin-down age for B assuming an initial spin period and braking index. Then, assuming a braking index for A, we compute the required initial spin period of A and the age of the system by asserting equation (2). As a starting point, hereafter known as model 1, we adopt a braking index for B based on observations of other normal pulsars (see, e.g., Kaspi & Helfand 2002, for a review) which are consistent with a flat distribution in the range $1.4 < n_B < 3.0$. Given the completely unknown braking indices for recycled pulsars in general, for A we took a more conservative approach and assumed a flat distribution in the range $0 < n_A < 5$. To show the effect of B's unknown initial spin period on the results, we performed all simulations using a flat distribution in the range $0 < P_{0,B} < P_B$ (dotted lines) and for $0 < P_{0,B} < 150$ ms (solid lines). The upper bound in the latter case is taken from the range of initial spin periods inferred from pulsars with multiple age constraints (see, e.g., Migliazzo et al. 2002; Kramer et al. 2003). The resulting initial spin period distribution for A peaks just below 20 ms and the age distribution peaks at ~ 50 Myr (i.e. B's characteristic age).

3.2 Exponential torque decay

Model 1 assumes no decay of the braking torque. An alternative solution to equation (1) can be found for the case where the braking torque K decays with time. Assuming, for simplicity, an exponential decay of the form $K = K_0 \exp(-t/t_{\text{decay}})$, where K_0 is a constant and t_{decay} is the $1/e$ decay time, equation (1) integrates to yield the so-called “reduced age”, i.e.:

$$t_{\text{reduced}} = t_{\text{decay}} \ln(1 + t_{\text{sd}}/t_{\text{decay}}). \quad (5)$$

Here, t_{sd} is described by either equation (3) or (4) depending on the assumed value of n .

The cause and even existence of torque decay in isolated non-recycled neutron stars is uncertain and controversial (see, e.g., Bhattacharya et al. 1992). In young neutron stars, it is thought to be due to either the decay of the magnetic field and/or the alignment of the spin and magnetic axes with time (see, e.g., Tauris & Konar 2001). Since torque decay is not thought to be significant for recycled pulsars after the accretion phase (see, e.g., Bhattacharya & van den Heuvel 1991), we consider only the case in which the torque on B decays. In models 2 and 3

the simulated distributions shown in Fig. 1 result from the equality $t_{\text{sd},A} = t_{\text{reduced},B}$ assuming pure magnetic dipole braking ($n_A = n_B = 3$) and a torque decay on B with a timescale of 10 Myr in model 2 and 100 Myr in model 3. In both cases, the time since spin-up ceased is smaller than for model 1, with the age distribution peaking at 20–30 Myr.

3.3 Interaction models

So far we have assumed the spin-down of both pulsars to be independent. In reality, as noted by Lyne et al. (2004), A's rate of loss of spin-down energy is 3000 times that of B; this, together with the close proximity of the two pulsars in their orbit, means that B's spin-down is significantly affected by A's relativistic wind. Direct observational evidence for such an interaction was presented by McLaughlin et al. (2004).

To model these effects, we follow the results of Lyutikov (2004) and consider two cases. In the first, hereafter model 4, it is assumed that all the Poynting flux from B is dissipated when it reaches the interface between A's wind and B's truncated magnetosphere. Using equation (9) from Lyutikov (2004) for this case, we find that

$$\dot{P}_B = k_1 \left(\frac{\dot{E}_A}{D^2} \right)^{1/3} P_B, \quad (6)$$

where k_1 depends on B's radius and intrinsic magnetic field, \dot{E} is the spin-down energy loss rate of A and D is the separation of the two pulsars. The basic spin evolution of B in this model implies a braking index $n_B = 1$ which is modified by A's spin-down energy loss. Such a dependence can also be found from the model of Arons et al. (2005).

In the second case put forward by Lyutikov (2004), hereafter model 5, the interface is partially resistive and large surface currents produced combine with a poloidal magnetic field of B to produce a spin-down torque. This process results in a relationship of the form

$$\dot{P}_B = k_2 \left(\frac{\dot{E}_A}{D^2} \right)^{1/2}, \quad (7)$$

where k_2 also depends on B's radius and magnetic field strength. In this case, the spin evolution of B is independent of its own period (corresponding to a braking index $n_B = 2$) and is completely dominated by A's spin-down energy loss.

To derive age constraints for models 4 and 5, we adopt a slightly different approach since equations 6 and 7 cannot be integrated analytically. Instead, we solve for the spin period evolution of B numerically assuming the parameters k_1 and k_2 to be constant. Starting with the currently observed spin parameters, we step back in time and calculate the variation of $\dot{E}_A = 4\pi^2 I_A \dot{P}_A P_A^{-3}$ using equation (1) to compute P_A and \dot{P}_A at each epoch. We assume the canonical neutron star moment of inertia $I_A = 10^{38}$ kg m². Simultaneously, we evaluate D using the results of Peters & Mathews (1963) and Peters (1964). During the calculation, we also keep track of whether A's wind continues to penetrate B's magnetosphere using equations (10) and (12) from Lyutikov (2004)¹. At the point when this condition is no longer met,

¹ Note that there is a missing c in the numerator of equation (10) of Lyutikov (2004) to calculate the magnetic field strength of B.

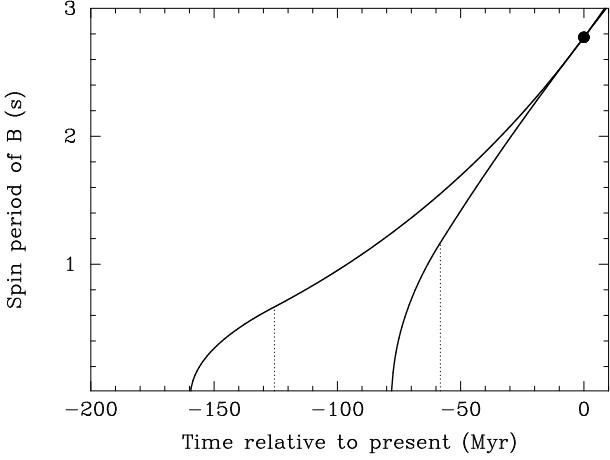


Figure 2. The spin history of B assuming two cases (left: model 4; right: model 5) of magnetospheric interaction from Lyutikov (2004). B’s current spin period and epoch is marked by the solid point at the top right. The vertical dotted lines in each case show the point at which A’s wind no longer penetrates into B’s magnetosphere (125 Myr for model 4 and 58 Myr for model 5).

we follow B’s spin evolution using the standard spin-down formula given in equation (1). Example evolution curves are shown in Fig. 2 for the case of underlying dipolar spin-down ($n_A = n_B = 3$).

The results of our Monte Carlo simulations for models 4 and 5 are shown alongside the other models in Fig. 1. Unlike the other models, the system age constraints depend strongly on B’s unknown birth spin period. Assuming B’s period was < 150 ms at birth, the age distributions peak sharply at 180 and 80 Myr respectively for models 4 and 5. For a broader range of initial spin periods, the system age becomes less well constrained. The reason for this can be seen in Fig. 2 which shows the large range of system ages possible for a given $P_{0,B}$.

4 DISCUSSION

We have considered a range of spin down models to place age constraints in the double pulsar system. A striking result of this study is the variety of possible system ages. These range from $\lesssim 20$ Myr (model 2) to almost 200 Myr (model 4). Models 1–3, which do not account for the effect of A’s wind on B, favour significantly smaller ages than models 4 and 5 which do account for the interaction. All models we considered favoured an initial spin period for A that is close to its currently observed value, with the peak of the distribution in the range 15–20 ms. This range is consistent with A’s initial spin period predicted by accretion spin-up models (see, e.g., Arzoumanian et al. 1999). Given the current evidence in favour of initial spin periods for normal pulsars to be < 150 ms (see, e.g., Migliazzo et al. 2002; Kramer et al. 2003), and for interaction between A and B (McLaughlin et al. 2004), we prefer the constraints provided by the solid lines for models 4 and 5 shown in Fig. 1.

Since the age of J0737–3039 determines its contribution to the coalescence rate of neutron star binaries, we briefly revisit the results of the calculations most recently carried out by Kim et al. (2006) where an age of 230 Myr was assumed.

Taking into account the additional time to coalescence of 85 Myr, estimates of the total lifetime of J0737–3039 in this paper range between 105 Myr and 265 Myr. From Table 1 of Kim et al. (2006), we find that the contribution to the global merger rate made by J0737–3039 would therefore either increase by 100% in the youngest case, or drop by 10% in the oldest case. In our opinion, the most realistic spin-down models we have considered are those which take into account the interaction, and assume that B’s initial spin period was negligible compared to its current value. For model 4, the estimated lifetime would be $\sim 80 + 85 = 165$ Myr, i.e. the merger rate contribution would increase by 40% over the value found by Kim et al., whereas for model 5, the contribution does not change significantly. Given the uncertainties in merger rate estimates, our results do not change the conclusions that binary neutron star inspirals are unlikely to be detectable by the current gravitational wave detectors. However, the prospects for detection by future instruments such as advanced LIGO are excellent.

Our results can be used to constrain the post-supernova orbital parameters in the double pulsar system. Using the formulae given by Peters & Mathews (1963) and Peters (1964) we find the mean orbital separation and eccentricity after the formation of B to be respectively 1.0×10^9 m and 0.14 for an age of 180 Myr favoured by model 4. For the 80 Myr solution from model 5, the corresponding numbers are 0.9×10^9 m and 0.11. These constraints in turn restrict the allowed ranges of system parameters at the time of the second supernova (Piran & Shaviv 2005; Willems et al. 2006; Stairs et al. 2006). We have repeated the analysis of Thorsett et al. (2005) who constrain the likely kick velocity at the time of the second supernova, V_k , the tilt angle between the pre and post-supernova orbital planes, δ , and the pre-supernova mass of B’s progenitor star, $m_{2,i}$. These simulations were carried out assuming the two different prior distributions of the current (unknown) radial velocity of PSR J0737–3039, as described in detail by Stairs et al. (2006).

We have imposed our two possible age solutions to the simulations described by Stairs et al. (2006) by restricting the age ranges considered to be either 70–90 Myr, or 170–190 Myr as opposed to the range of up to 100 Myr originally considered by Stairs et al. (2006). In general, we obtain consistent results to Stairs et al. (2006) which indicates that their work does not critically depend on the system age. The only exception is the 70–90 Myr simulation assuming the Gaussian radial velocity distribution, for which the age constraints favour slightly lower $m_{2,i}$, V_k and δ values than the unconstrained case. The new age constraints derived here are fully consistent with the idea that B’s progenitor was a low-mass star, and that the system received a relatively small impulsive kick at the time of the second supernova (Podsiadlowski et al. 2005).

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